PECAN ROOT GROWTH AND DEVELOPMENT[1]

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INTRODUCTION

The relation of the root system of pecan trees, *Hicoria pecan* Britt., to nursery and orchard practices has been studied at the Georgia Agricultural Experiment Station for several years.[2] The relation of mycorrhizal infection to the growth of pecan roots has also been studied.[3] The present paper deals with certain morphological, physiological, and anatomical characters of pecan roots as they relate to growth and development.

Data are also being obtained on the most suitable depth of setting trees, distance between, depth of cultivation, season of cultivation, and methods of fertilizing and cover-cropping orchards.

The gross morphology of pecan roots was studied by digging the roots and charting their position on coordinate paper as they were being dug. Some were dug with the specific purpose of studying the tap root, others were dug to examine lateral roots, and still others to examine the fibrous roots. Some trees were grown under controlled conditions and the roots were examined before they were a year old; some were dug from nurseries, and others from orchards that had been bearing for many years.

An attempt was made to dig trees that had been grown on the prevailing soil types found in Georgia, as well as in different locations with respect to water table and drainage. Likewise, artificial soils were prepared and roots were grown in them, the roots being removed later for examination.

Studies on the development of new roots were made by giving specific treatment to a part or all of a tree or root before it was planted; portions were then dug periodically for examination. Studies of growth rate were made by growing seedlings in boxes with glass sides. When the boxes were inclined the roots grew close to the glass on the inside and could be measured accurately, and as often as desired. The glass was fitted with heavy oilcloth on the outside to keep out the light, and most measurements were made at night.

THE SPREAD OF PECAN ROOTS IN THE SOIL

The crowding of pecan roots between adjacent trees begins much earlier than the crowding of branches of the same trees. Figures 1 and 2 show the relation of height and spread of branches to depth and spread of roots. This subject was discussed at length in a previous publication.[4]

[1] Received for publication Sept. 22, 1933; issued October 1934. Paper no. 39, Journal Series of the Georgia Agricultural Experiment Station.
[2] Woodroof, J. G. THE RELATION OF THE ROOT SYSTEM OF PECAN TREES TO NURSERY AND ORCHARD PRACTICES. Ga. Expt. Sta. Bull. 176, 15 pp., illus. 1933.
[3] Woodroof, N. C. PECAN MYCORRHIZAS. Ga. Expt. Sta. Bull. 178, 26 pp., illus. 1933.
[4] Woodroof, J. G. See footnote 2.

The first year the top branches very little and grows to a height of about 1 foot. The taproots grow from 1 to 3 feet, depending on the soil fertility, moisture, and texture. Branching of the seedling taproot extends throughout its length, but often a high percentage of these small laterals die during the fall of the first year. The second year the distribution of growth is very similar to that of the first, considerable branching occurring in both top and roots. The taproot reaches a depth of about 4 feet, and the laterals make considerable growth in the horizontal direction. Typical mycorrhizal roots are usually formed first during the second year.

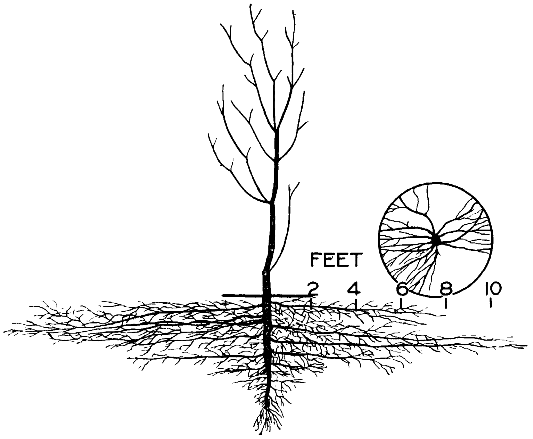

FIGURE 1.—A 6-year-old pecan tree with a spread of branches 5½ feet, a height of 13 feet, a root spread of 24 feet, and a root depth of 6 feet. Trees of this size are frequently transplanted into an orchard, in which case the roots are cut back to a spread of about 1 foot. In the circle is shown the orientation of the 11 largest lateral roots.

During the third year the height of tree, depth of taproot, and spread of laterals are about equal, but the branch spread is considerably less. This is the age at which most trees are transferred from the nursery to the orchard. In the fourth year the height of tree exceeds the depth of roots for the first time, and the spread of the roots is about double that of the branches.

Little additional deepening of the roots occurs after 5 years, but the tree continues to grow in all other directions. By the time a tree is 10 years old the height of the top is about four times the depth of the taproot, and the spread of the branches is about one-half the spread of the roots. Branching of both stems and roots is more pronounced as the tree grows older, and at 20 years or more the tree is made up almost entirely of branches both above and below ground.

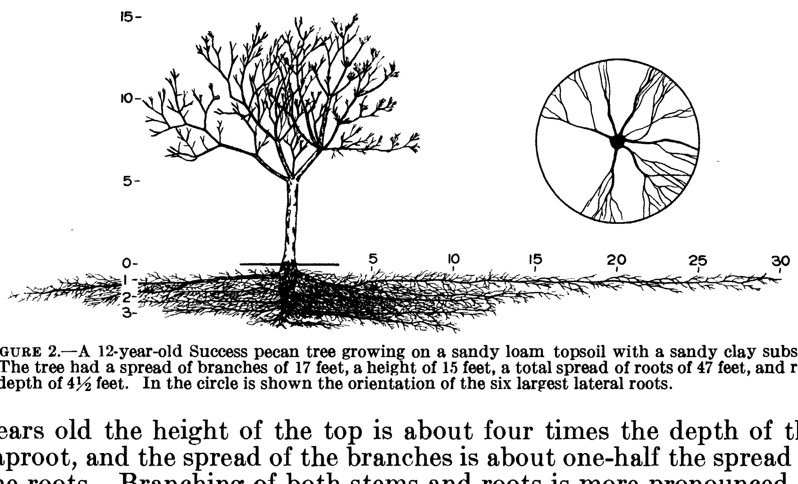

FIGURE 2.—A 12-year-old Success pecan tree growing on a sandy loam topsoil with a sandy clay subsoil. The tree had a spread of branches of 17 feet, a height of 15 feet, a total spread of roots of 47 feet, and root depth of 4½ feet. In the circle is shown the orientation of the six largest lateral roots.

Pecan roots tend to grow most profusely in those areas or strata of soil in which conditions are most favorable for growth. In a cultivated orchard the region in which roots are most dense is usually from 12 to 18 inches below the soil surface. Deep cultivation tends to force the roots to lower levels, while shallow cultivation, a high water table, or mulch with litter or cover crops allows the roots to grow near the surface. Fibrous roots tend to grow toward the soil surface until they are hindered in doing so by drought, freezes, cultivation, or other deterrents.

Pecan roots may be divided into the following classes: (1) Taproots, which grow straight down and determine the depth of penetration of the roots under the particular conditions; (2) lateral roots, which usually grow in a horizontal direction straight from the tree at a depth of from 1 to 2 feet, and determine the lateral spread of roots under the existing conditions; (3) fibrous roots, which grow in all directions from the laterals. Fibrous roots are subject to constant dying and replacement as a result of varying growing conditions; mycorrhizal roots, which are a type of fibrous roots and grow in dense masses throughout the entire area in which roots are growing.

ROOT GROWTH UNDER VARIOUS ENVIRONMENTAL CONDITIONS

With abundant moisture and the approach of warm weather in the spring, roots of all orders make vigorous growth with moderate branching. Roots sometimes grow 10 cm without branching, then produce 4 to 6 branches while making 5 to 10 cm more growth. The branches run in different directions, each of them growing from 4 to 10 cm, then beginning to branch. As the season advances growth is less vigorous and branching more profuse.

The spring growth of roots begins a little in advance of the spring growth in shoots. Roots are more sensitive to adverse conditions either of the soil or weather but are also more responsive to the return of favorable conditions. Therefore roots usually make from 4 to 8 cycles of growth during the year.

EFFECTS OF MOISTURE, LIGHT, AND SOIL TEXTURE

Table 1 shows the relation of root order and root diameter to daily growth and represents the results of more than 1,700 measurements. These were made on young seedlings only, but an approximate relationship between size of root and rate of growth appears to hold for all roots.

Roots are very efficient in making use of the moisture supplied to the soil by a relatively light summer rain. They also respond to the heat supplied by the sun during the first warm days of spring several weeks before there is any response in growth in the shoots.

Eighteen taproots of young seedlings exposed to reflected sunlight for 2 weeks had an average daily growth of 9.5 mm. The same roots when kept in total darkness for a week had an average daily growth of 8.5 mm. The same roots were killed by direct exposure to the sun during the following week. The seedlings were growing in a tall box with a glass side, and the soil moisture was kept as constant as possible throughout the period of the experiment.

Figure 3 represents six taproots, drawn to scale, showing typical modifications in form caused by differences in soil texture and moisture content. These roots varied in depth from a little over 3 to 9

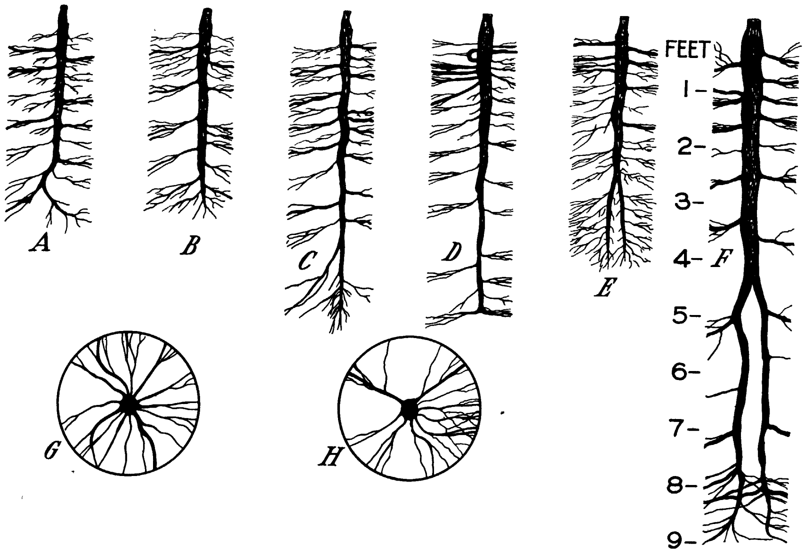

FIGURE 3.—*A–F*, taproots of six pecan trees, showing how their form was modified by different soils. The type of subsoil caused a variation in the length of taproot from a little over 3 feet to more than 9 feet. The length of taproot was not influenced by age of tree (after 3 years) nor the spread of branches. *G*, *H*, orientation of the lateral roots.

feet. When the soil was loose, coarse, or poor in nutrients, or when the water table was low the taproot has been found to penetrate to a depth of 10 or more feet.

TABLE 1.—*Relation of root order and root diameter to the daily growth rate in pecan trees*

Root order	Diameter of roots	Number of roots making indicated growth in millimeters												
		0	1	2	3	4	5	6	7	8	9	10	11	12
	Millimeters													
Taproots	2–3	0	0	1	1	4	15	16	20	30	39	58	40	49
First-order laterals	½	135	198	270	191	191	136	18	8	12	4	2	5	0
Second-order laterals	¼–½	0	50	21	0	0	0	0	0	0	0	0	0	0

Root order	Diameter of roots	Number of roots making indicated growth in millimeters												
		13	14	15	15	16	17	19	20	21	22	23	24	25
	Millimeters													
Taproots	2–3	64	46	33	30	18	15	12	9	3	2	4	0	1
First-order laterals	½	0	0	0	0	0	0	0	0	0	0	0	0	0
Second-order laterals	¼–½	0	0	0	0	0	0	0	0	0	0	0	0	0

Roots that form at right angles directly from the taproot are laterals of the first order; those arising directly from these are laterals of the second order, and so on.

Lateral roots of the first order of 6-week-old seedlings were measured at 48-hour intervals for rate of growth. They had about 12 laterals each, the oldest being about 15 cm long and growing less than 0.2 mm per day. The most vigorous laterals grew from 3 to 9 mm per day when about 6 cm in length. The youngest laterals grew less rapidly. Thus each lateral began growth at less than 0.2 mm per day, rapidly increased to 1.0 mm, and finally to 10 mm on about the tenth day. After 2 weeks, growth was gradually retarded, finally stopping in less than a month. This cycle is apparently followed by

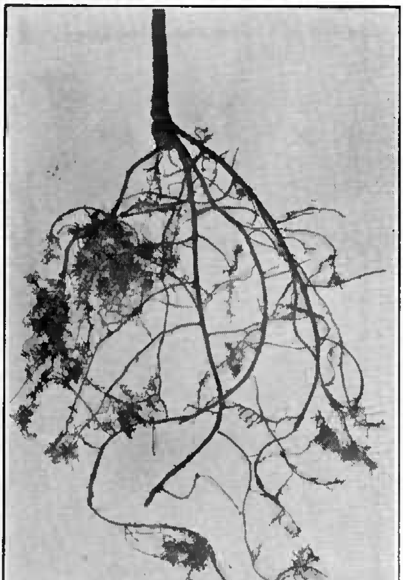

FIGURE 4.—Sinuous growth of pecan roots.

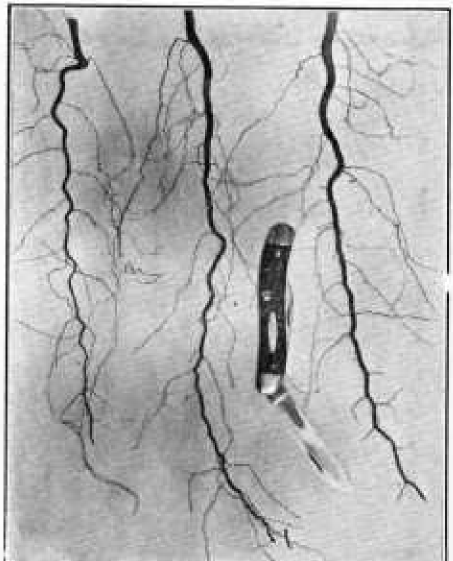

FIGURE 5.—A pecan root that was cut and gave rise to a number of branches; the smallest roots are mycorrhizal.

all laterals of the first order. Those occupying a zone of from 20 to 40 cm back of the tip of the taproot were most active, while those either closer to or further from the tip made less rapid growth.

Lateral roots are at first long and slender, performing the function mainly of absorption. But as they increase in age and size they become organs of storage and support, functions which they maintain throughout their existence. As they in turn produce feeding roots they act as conductors of material to and from the taproot.

While lateral roots tend to grow straight from the taproot, their course is practically never direct. There are always crooks, bends, or twists which give the laterals slack (fig. 4). When lateral roots are caused to turn from a straight course they often produce branches on the convex side.

Lateral roots give rise to hundreds of branches. These grow in every direction, producing thousands of very fine, much-branched fibrous roots that thoroughly permeate the soil. Many are mycorrhizal roots. Figure 5 illustrates the branching of fibrous roots.

EFFECTS OF ATMOSPHERIC AND SOIL TEMPERATURES

The response of roots in dry soil to a renewed moisture supply is remarkably rapid. Following a drought of 2 months, a 0.69-inch rain wet soil in the open field to a depth of about 5 inches. Roots from trees of all ages clearly showed new growth to a depth of the moist

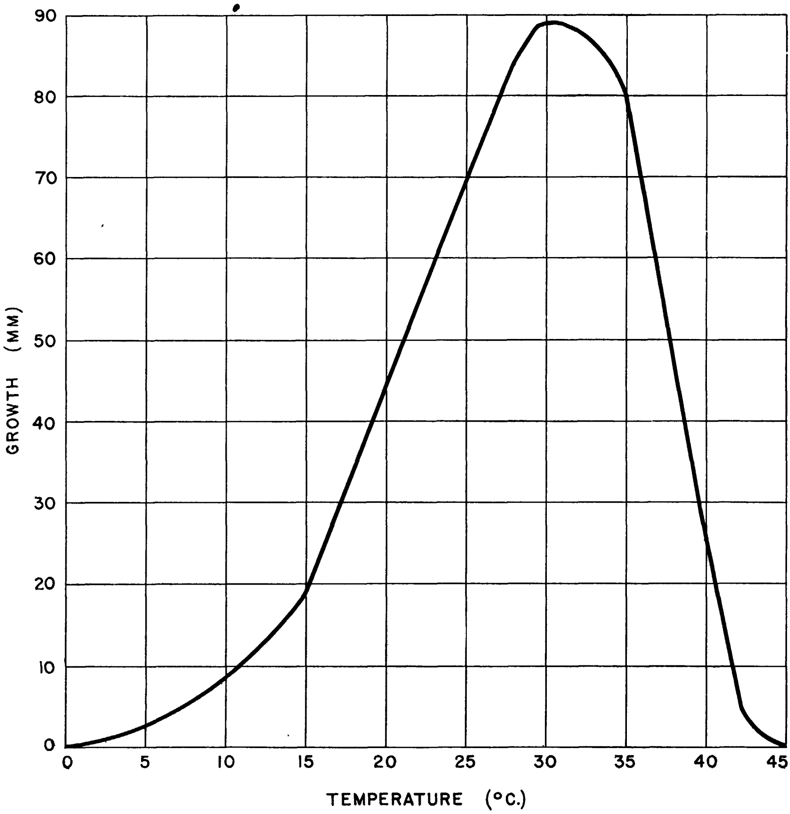

FIGURE 6.—Amount of growth made by 10 taproots when subjected to various temperatures for 24 hours.

soil but none below that point. Roots grew from 2 to 4 mm within 24 hours after the rain. The rain came from the east, causing the soil on the east side of the trees to become wetter than that on the west side. Counts of the growing points per cubic foot of surface soil on the west and east sides of the tree, at the end of the branches, were 1,500 and 32,000 respectively.

Pecan roots were examined immediately after the atmospheric temperature had been −7° C. on three successive nights. The surface soil froze each night but warmed to about 4° at noon. Immediately below the 3 surface inches the soil temperature was maintained at between 4° and 7°. At lower depths the temperature was slightly higher. After carefully studying the soil depth, soil temperature, and root growth, it was found that no growth was evident in the soil area that had been frozen for three successive nights; a feeble growth of roots occurred in the area that was maintained at from 4° to 7°; and slightly more growth was found in lower areas of soil.

Further study of the effect of temperature on root growth was made by carefully removing soil from an area 1 foot deep, 1 foot wide, and 2 feet long, from beneath both Alley and Frotscher trees, at 15-day intervals for a year. The soil was washed through a screen and the new root growth measured. While there was no close relation between the amount of root growth and the temperature, it was evident that some root growth occurred throughout the entire winter.

The amount of growth made by roots at various temperatures was studied also under controlled conditions. Nuts were germinated in soil. The seedlings were then removed from the soil, measured, and transferred to compost in paraffined, paper-board quart cans. From 4 to 10 seedlings were placed in each can, with soil and a definite amount of moisture. The cans were placed in constant-temperature chambers ranging from −2° to 45° C. Water was added as needed, holes in the bottom allowing the excess to drain out. After 4 days the seedlings were removed from each can and the increase in length of tap roots measured. Forty-two lots were used, including 5 series and 23 different temperatures. The results are shown in figure 6 and table 2.

TABLE 2.—*Influence of temperature on root growth of pecans*

[10 roots observed for 4 days]

Temperture (° C.)	Growth in length	Condition of roots at end of period	Temperature (° C.)	Growth in length	Condition of roots at end o period
	Millimeters			*Millimeters*	
−2	−2.00	Entire roots dead.	23	62.0	Roots uninjured.
−1	.15	Root tips dead.	24	69.0	Do.
1	1.4	Roots uninjured.	27	81.1	Do.
3	5.2	Do.	30	88.1	Do.
6	4.6	Do.	33	73.1	Do.
9	7.6	Do.	34.5	70.7	Do.
12	11.3	Do.	36	57.0	Do.
13	13.1	Do.	38	37.8	25 percent of tips dead.
14	14.3	Do.	41.5	10.0	All root tips dead.
15	18.6	Do.	43	−5.0	All roots injured; top uninjured.
18	41.2	Do.			
21	56.0	Do.	45	[1]	Tops almost dead.

[1] Dead.

Growing roots were killed at a temperature of −2° C. or lower. Growth increased slowly as the temperature was raised from 0° to about 15°; from 15° to 30° the rate of increase was very rapid. Further increase in temperature slowed down growth until 38° was reached. At that temperature growth was very slow, and at the end of the 4-day period most of the growing tips were dead. At 42° all tips were killed, while the older portion of the roots and tops were uninjured; at 45° all roots were killed and the tops showed slight injury during the period of the experiment.

These results show that roots remained alive and made some growth over a range of temperature from 0° to 38° C. and were killed at temperatures below −2° or above 45°. Rapid growth was made at temperatures ranging from 21° to 36°, reaching a peak at 29°.

It will be noted from figure 7 that the soil temperature at 1 foot below the surface was above 21° C. during July, August, and Sep-

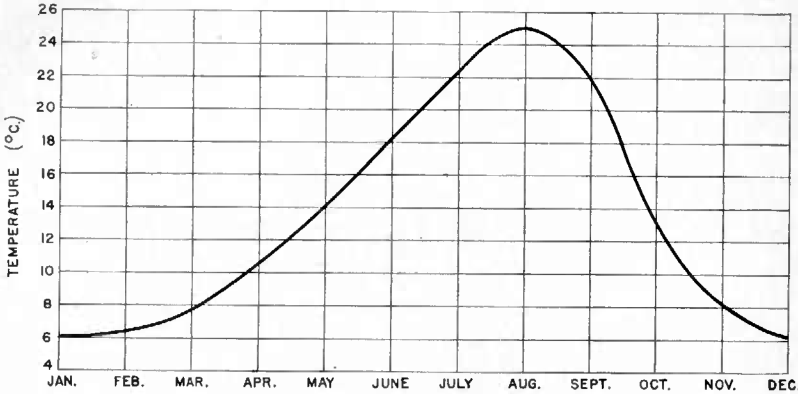

FIGURE 7.—Temperature of the soil in pecan orchard 1 foot below the surface throughout the year.

tember only, and at no time did it quite reach a temperature sufficient to promote maximum growth. It may also be noted that at no time did the soil become cold enough, by a margin of 5°, to stop growth 1 foot below the surface.

FIGURE 8.—Orientation of latera lroots of a pecan tree 10 years of age.

Roots about the base of 10-year-old and 5-year-old pecan trees were exposed by digging the soil away for a depth of 2 feet and a radius of 4 feet, as shown in figure 8. Most roots from which the soil was dug in the spring continued to grow throughout the summer. Those less than 1 mm in diameter died from drying, within a few days, and a few larger roots died when the weather became very hot, but all of those more than about 5 mm in diameter withstood the extreme heat and dryness of summer.

The exposed roots became harder and more brittle the longer they were exposed. The cortex developed the appearance of the cortex of stems and the secondary phloem developed chlorophyll. All of the exposed roots were killed by freezing the following winter. However, none of the roots that were cold-killed died beyond the region exposed. In some cases the cutting sent up one or more shoots, thereby growing independently of the parent plant.

THE ANATOMY OF PECAN ROOTS

It is believed that a knowledge of the anatomy of the pecan roots can be applied to other tree species and that certain facts heretofore little recognized may aid in explaining problems of general application. This is especially true of the relationship of mycorrhizal fungi to the host roots. Of even greater importance is the variation in reaction of the different classes of roots to environmental conditions, especially with relation to soil moisture.

ROOTS OF THE PRIMARY PLANT BODY

All newly formed roots, regardless of size, that have not developed secondary thickening constitute the primary plant body. Such roots are always present on trees in a state of growth.

Very young pecan roots may be divided into large and small roots. each class possessing distinct anatomical characters in the primary plant body. The principal characteristics of the two types are summarized in table 3.

TABLE 3.—*Summary of the anatomical characteristics of small and large roots of the pecan*

Characteristics	Small roots	Large roots
Root cap	Only a few cells thick	Many cells thick.
Root hairs	Wanting	Wanting.
Epidermis	do	Indistinctly developed.
Cortical parenchyma	4–6 cells thick	20–40 cells thick.
Endodermis	12–16 large cells in cross section	40–100 small cells in cross section.
Pericycle	One layer of cells thick	Usually more than 1 layer of cells thick.
Primary xylem	Diarch or triarch	Pentarch to octarch.
Primary phloem	Same number of strands as in xylem of the same root.	Same number of strands as in xylem of the same root.
Pith	Absent	Present in taproots only.
Procambium	Present	Present.
Secondary thickening	May occur	Usually occurs.
Periderm	do	Do.
Length	1–10 mm	0.5–30 cm.
Diameter	0.20–0.25 mm	2–6 mm.
Mycorrhizas	Usually present	Seldom present.

Small roots are more numerous than large roots and in trees more than 1 year old are usually associated with mycorrhizal fungi. They are shorter and smaller in diameter than nonmycorrhizal roots. Large roots are comparatively thick and long, smooth, white, and usually without fungus infection (fig. 9).

A young growing nonmycorrhizal root is bluntly pointed and increases in thickness as one measures from the tip. The tips of mycorrhizal roots are usually rounded (fig. 10).

Regardless of the length of a root, all increase in the thickness of the primary plant body is attained within 2 to 8 mm of the tip, depending upon the size of the root. The extent in length of the region of enlargement is about twice the diameter of the individual root. There is an overlapping of the regions of enlargement and elongation, the latter being limited to a region of from 1 to 6 mm from the tip (fig. 9). The extent of both regions varies with the diameter of the root. In mycorrhizal roots both processes are confined to a region of less than 2 mm.

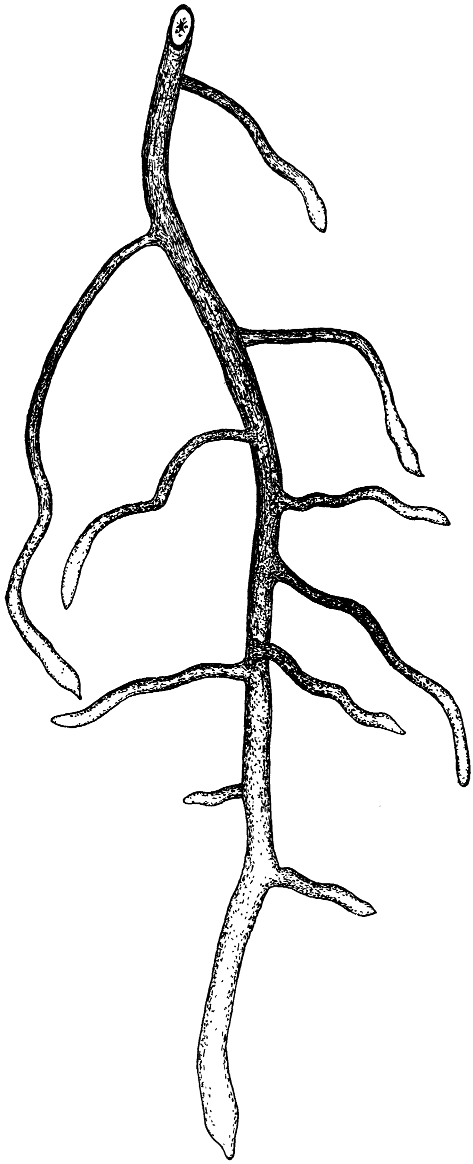

FIGURE 9.—Group of pecan roots showing absence of root hairs; the growing points are white and larger than the older portions.

ROOT CAP

A root cap is present on most growing pecan roots, but certain ephemeral nonmycorrhizal roots of the third and fourth orders have very poorly developed or no root caps. In longitudinal section the root cap appears as a parabola and consists of nonnucleate cells with firm walls (fig. 11). The cells of the root caps are renewed from a centrally located group of meristematic cells. Mycorrhizal roots, when rather large, have a cap similar to that of nonmycorrhizal roots, but usually they are bluntly rounded and only 2 or 3 cells thick. The cap is covered with the fungous mantle, which protects the outer cells from wearing away in the course of growth in the soil.

ROOT HAIRS

Root hairs are not present on roots of pecans (figs. 9 and 11). While the writers observed an occasional epidermal cell "bulging" above the surrounding cells, several thousand examinations of roots growing under widely different humidity and temperature conditions have not revealed a single root with typical root hairs.

Epidermis

The region just back of the cap of the growing root is bound by relatively small, cylindrical parenchymal cells. The several layers directly beneath are very similar, though the cells are slightly larger. Thus, if an epidermis is present, it does not differ markedly from the cells immediately beneath. This outer layer of smaller cells is always absent from mycorrhizal and other small roots (fig. 12, *A* and *B*).

The outermost 2 or 3 layers of cells tend to act as a unit and do not develop intercellular spaces. After the cortex has collapsed and

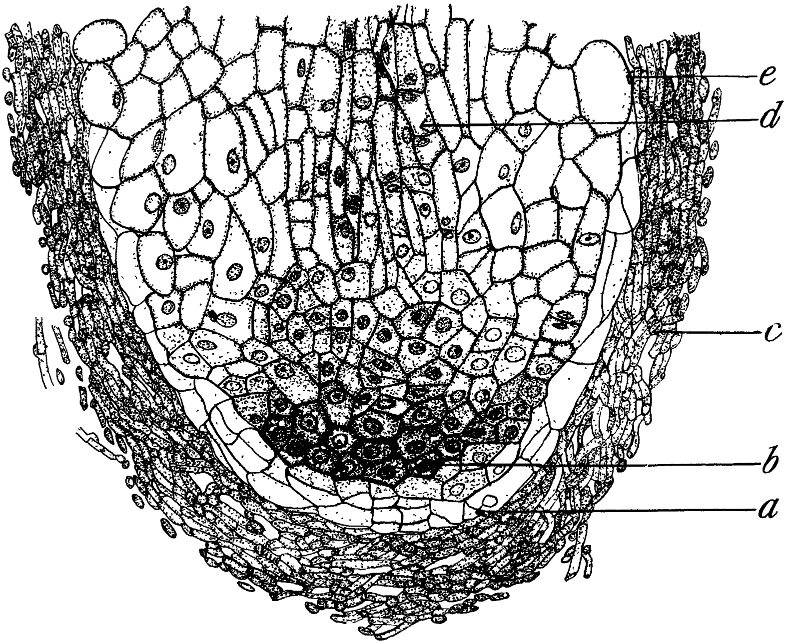

FIGURE 10.—Tip of a rapidly growing mycorrhizal root: *A*, Root cap; *B*, region of rapid cell division; *C*, fungous mantle; *D*, early cell elongation in region of central cylinder; *E*, early formation of cortical paren chyma. ×740.

there are no structural remains of the cortical parenchyma this region covers the root as a black wrinkled tissue.

Cortical Parenchyma

The cortical parenchyma is made up of thin-walled, parenchymal cells which are irregularly rounded with intercellular spaces between. The cells near the center of the region are the largest, and those on either side progressively smaller. The layer varies in thickness from 4 to 6 cells in mycorrhizal roots to from 20 to 40 cells in large roots, as is shown in table 3. The thickness of the cortex is the most variable character in pecan roots and is influenced to some extent by soil moisture, temperature, and the amount and nature of the nutrients. The life of the region is about 2 weeks (fig. 13).

The breaking down of the cortex is accomplished by dissolution of the walls, first, of cells near the endodermis, followed by the disintegration of cell walls and cell contents throughout the entire region. On taproots the entire primary bark usually splits longitudinally, exposing the secondary phloem in streaks. Such splitting has been observed only in roots with a pith. As a result of the breaking down of the cortex young roots are thicker at points near their tips than at points farther away.

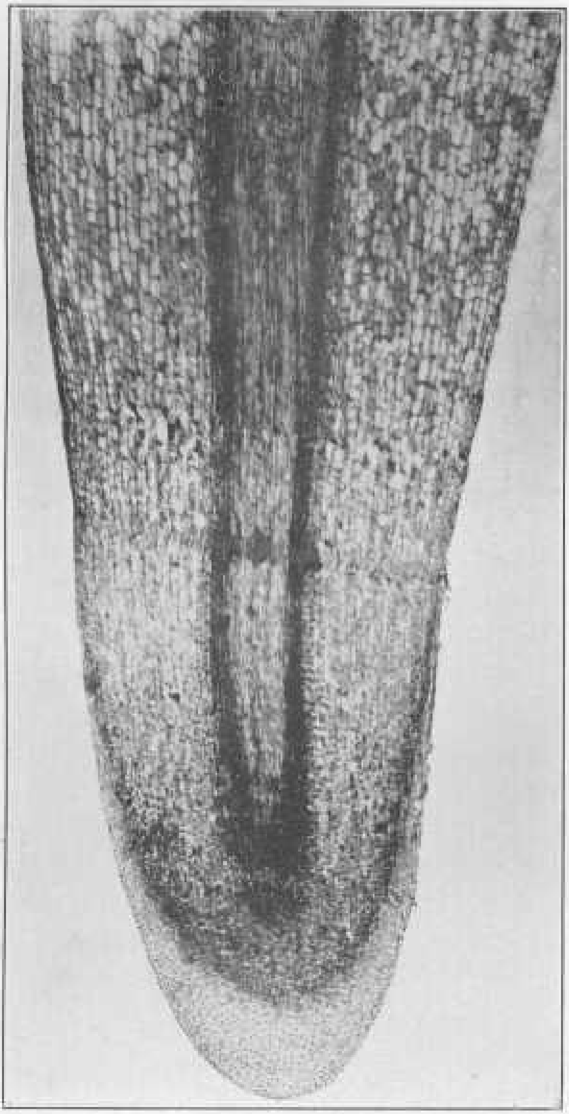

FIGURE 11.—Longitudinal section of root tip, showing the cap and other regions.

ENDODERMIS

The endodermis consists of a single layer of closely fitted, cylindrical cells which completely inclose the stele. In cross section from 14 to more than 100 cells may be observed in this region, depending upon the size of the root. On reaching full size the cells usually become filled with a gummy material, the origin and nature of which has not been fully determined (fig. 12, *C*).

PERICYCLE

The pericycle lies directly beneath the endodermis and varies in thickness in large and small roots. Mycorrhizal and other small roots have only a single layer of cells in the pericycle, while in large roots it is 2 or 3 cells in thickness.

In the formation of branch roots tangential cell division is initiated in the pericycle opposite a strand of xylem. Cell multiplication and emergence of the new root take place in the usual manner. Apparently not all of these roots emerge at once, but some may remain latent and again become active when the tips of the parent root have been killed by adverse growing conditions. This method supplements the formation of new roots by callus formed at the base of dead root tips.

Primary Xylem and Phloem

Primary xylem and phloem develop simultaneously through specialization of primordial meristem cells in a manner typical of dicotyledonous plants. In pecans the number of xylem strands varies with the size of the root, thickness of the cortex, and root order, and is indirectly influenced to some extent by soil temperature, soil moisture, and fertility. The number of strands may vary in a

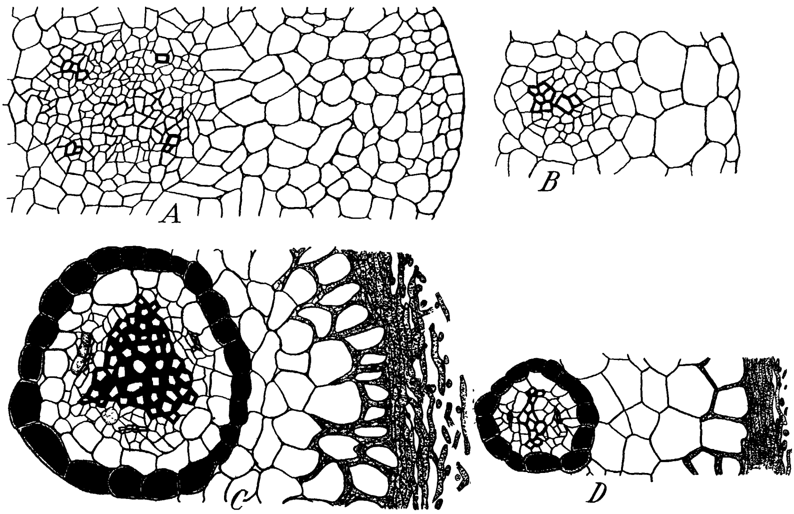

Figure 12.—Segments of cross sections of four pecan roots: *A*, Early stage in the formation of a tetrarch xylem in a large root; *B*, early stage in the formation of a diarch xylem in a small root; *C*, mycorrhizal root with a triarch xylem and well-differentiated primary phloem, pericycle, and endodermis; *D*, mycorrhyzal root with diarch xylem and well-differentiated primary phloem, pericycle, and endodermis.

single taproot from 5 to 12 by converging or dividing of the existing strands (fig. 14). The normal number of strands in a taproot appears to be 8, occupying the positions shown in figure 14, *K*. Unless growth is maintained at a rapid rate the number may drop to 7, 6, or 5. The presence of a pith seems to prevent further converging. Under some conditions one or more strands may divide and become double or treble, as shown in figure 14, *L*. In counting, the double or treble strands were considered as one.

The number of xylem strands in lateral roots is much more variable than in taproots. Pith is commonly absent, and the entire central part of these roots is primary xylem. In the absence of pith the number of strands may be reduced to as few as two. The number of strands of primary phloem corresponds to the number of strands of primary xylem, except that in cases of multiple strands of the latter, the phloem strands do not multiply correspondingly.

From tables 4 and 5 it is seen that the largest roots, with the largest stele, the greatest number of xylem strands, and the thickest cortex are associated with the presence of pith and absence of mycorrhizas. Likewise the smallest roots, with the smallest stele, the least number of xylem strands, and the thinnest cortex, are associated with the absence of pith and usually with the presence of mycorrhizal fungi. However, comparison of the anatomy of infected and uninfected small roots shows that the anatomy of small roots is not influenced by the presence of mycorrhizal fungi. Pith is present in taproots as an extension of the pith of the stem, but apparently the pericycle seldom, if ever, gives rise to a root with pith. The cells in the center of the pith region are the largest, and those surrounding are progressively smaller. They remain turgid and are usually filled with starch.

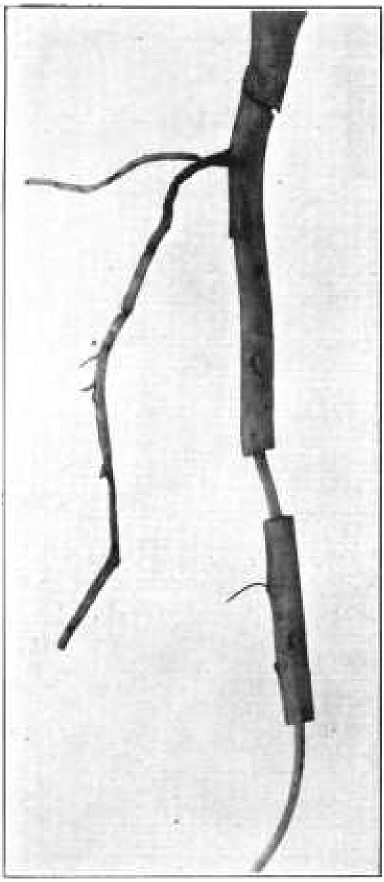

FIGURE 13.—Young pecan root with cortex partially removed, exposing the stele; the cortex sloughs off when the root is from 2 to 3 weeks old.

The cambium of pecan roots possesses a marked ability to produce callus tissue in the event of injury. This occurs when stems and roots are grafted or when root cuttings are made. Wounds made by cultivating implements also stimulate callus formation and subsequent formation of new roots or stems or both.

The cells of the secondary xylem are used for the storage of food materials, chiefly starch and water. About 60 percent of the number of cells and 90 percent of the total volume of secondary xylem are filled with starch during the greater part of the year. This region is the "wood" of roots and is more bulky, softer, and lighter in color and weight than the corresponding wood of stems. On complete drying the former lost 49.8 percent in weight as compared with 31.7 percent for the stems.

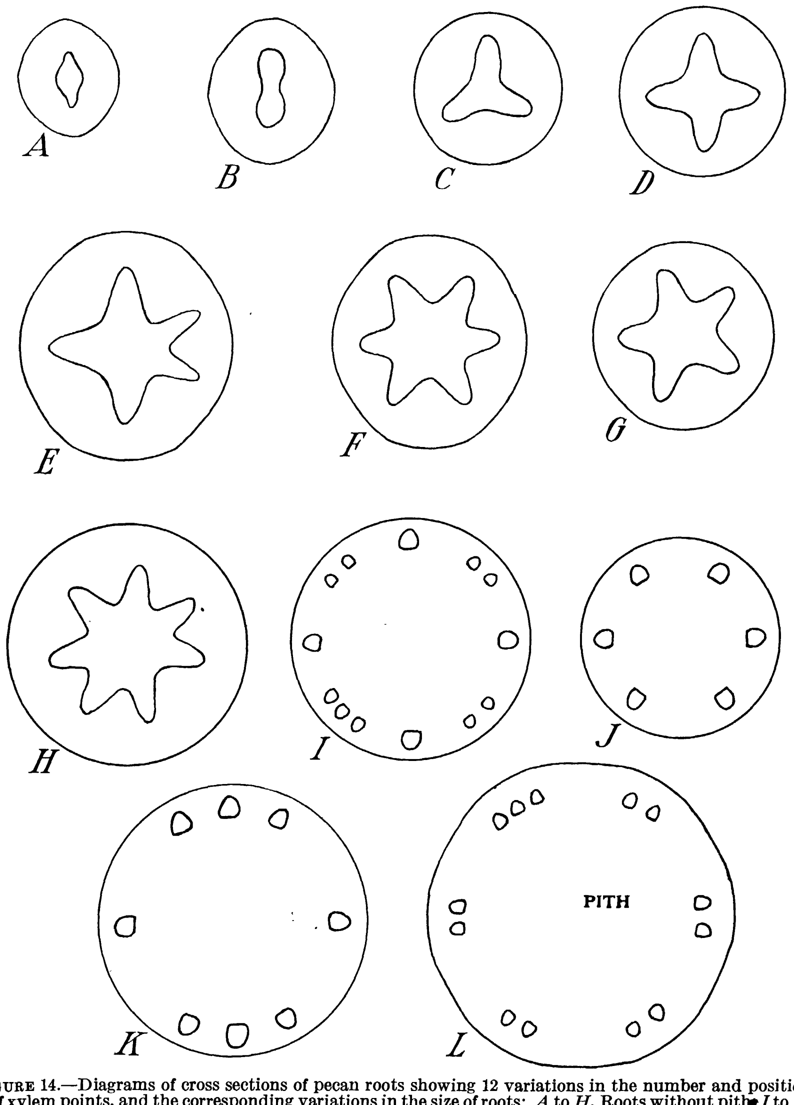

FIGURE 14.—Diagrams of cross sections of pecan roots showing 12 variations in the number and position of xylem points, and the corresponding variations in the size of roots: *A* to *H*, Roots without pith; *I* to *L*, taproots with pith; *E*, *I*, and *L*, multiple xylem strands; *K*, position of the strands in a taproot as it emerges from the shell.

TABLE 4.—*Variation in number of xylem strands in various classes of pecan roots*

Kind of roots	Number of xylem strands in roots having indicated stelar points [1]										
	Small roots			Large roots							
	2	3	4	5	6	7	8	9	10	11	12
Tap	0	0	0	0	16	8	61	13	12	2	1
Nonmycorrhizal	6	5	31	34	16	2	1	0	0	0	0
Mycorrhizal	43	26	6	0	0	0	0	0	0	0	0

[1] In studying the number of points in the stelar figure, roots were considered as belonging to 1 of the 3 classes in table 4. All taproots naturally fall in the general class of large roots, while all mycorrhizal roots naturally fall in the class of small roots. Nonmycorrhizal roots are extremely variable in size and thus fall in both classes. 8 appears to be the normal number of xylem strands in taproots, 2 of the normal number for mycorrhizal roots, and 4 and 5 for nonmycorrhizal roots.

TABLE 5.—*Relation of number of xylem points, root diameter, stele diameter, and thickness of cortex to the presence of pith and mycorrhizas*

[About 300 roots were measured]

Points in stelar figure	Diameter of root	Diameter of stele	Thickness of cortex	Pith	Mycorrhizas
	Millimeters	*Millimeters*	*Cells*		
8 [1]	3.01	1.56	21	Present	Absent.
7 [1]	3.49	1.78	29	do	Do.
6 [1]	2.43	1.08	19	do	Do.
6	2.35	.50	25	Absent	Do.
5	2.02	.45	20	do	Do.
4	1.52	.29	15	do	Do.
3	.25	.09	5	do	Present.
2	.20	.05	4	do	Do.

[1] Taproots.

As wood in roots is in the process of formation practically throughout the year, annual rings are less distinct than in stems. Heart-

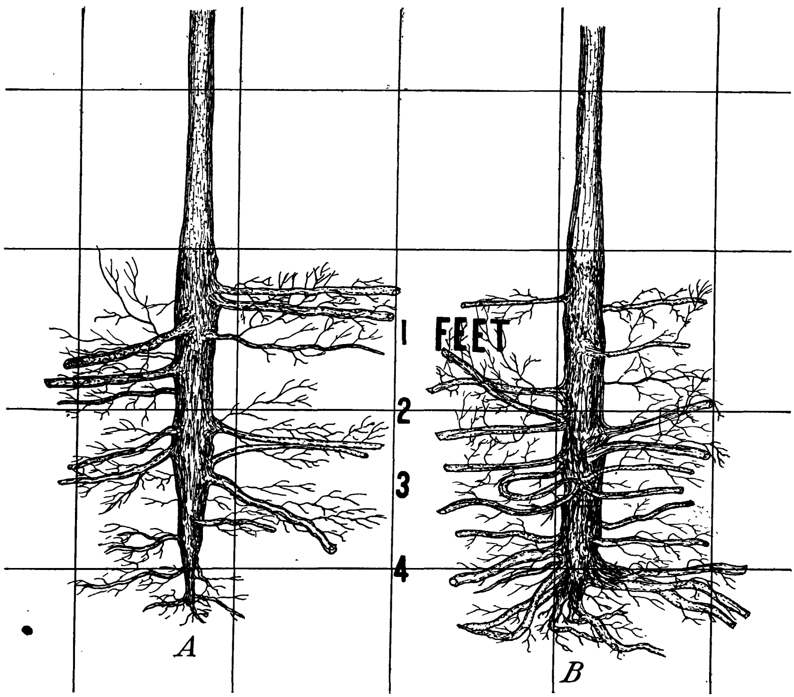

FIGURE 15.—Comparison of the orientation of lateral roots on transplanted and nontransplanted pecan trees. The nontransplanted tree *A* had 11 main laterals, while the transplanted tree *B* had 21.

wood is seldom found in pecan roots, which, when subjected to the proper conditions, decay very rapidly. The scant lignification of cell walls, the almost entire lack of tyloses, together with abundant starch and water in the xylem, afford an excellent medium for rot-producing organisms and host for insects.

Medullary cells originate from specialized cambium cells which give rise to phloem ray cells on the outside and xylem ray cells on the inside by tangential division. There are two types of ray cells in pecan roots. The most common type of cells, as seen in cross section, is about twice as long as wide, thin-walled, and always filled with starch. Cells of the other type are about 10 times as long as wide, thin-walled, and occur in groups adjacent to the larger storage cells. The latter may or may not be used as a place of storage.

ROOT DEVELOPMENT OF TRANSPLANTED TREES

Practically all of the bearing pecan trees in the southeastern part of the United States are nursery-grown trees and were transplanted when from 3 to 6 years old. The advantages and disadvantages of this practice have not been fully studied.

The roots of several 5-year-old and 10-year-old pecan trees were dug for examination at the same time that an equal number of transplanted trees were dug. Figure 15 shows representative root systems of the two groups of trees. Differences in the depth of penetra-

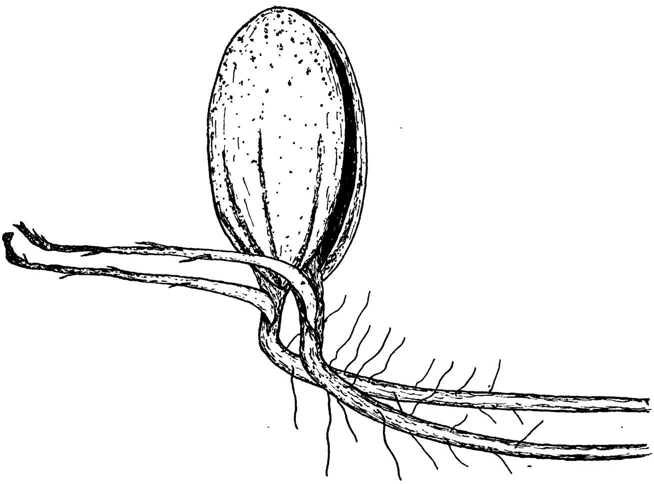

FIGURE 16.—Single pecan nut with 2 embryos giving rise to 2 taproots and 2 tops.

tion or size of the aboveground portion were not significant, the check in growth subsequent to transplanting being completely overcome within 2 or 3 years.

ABNORMALITIES IN PECAN-ROOT GROWTH

Normally a pecan germinates by splitting the shell in half at the apical end and both radicle and plumule emerging at once, but growing in opposite directions. In the course of these studies several types of abnormal behavior or roots have been observed.

MULTIPLE RADICLES

Of 10,000 germinating nuts that have been examined, about 1 out of each thousand has produced a multiple radicle (fig. 16). This character has not been correlated with any morphological character in the shell and therefore cannot be detected without either cracking or germinating the nut. Usually the 2 radicles emerged from the shell at about the same time, but when there were 3 or more they varied widely in size and time of emerging from the shell.

MULTIPLE PLUMULES

About 1 out of 2,000 nuts when germinated has given rise to 2 plumules. More than 2 plumules have never been observed as coming from one nut. Often it was quite difficult to determine whether the nut produced 2 plumules or produced 1 plumule which later branched. All nuts which produced multiple plumules also produced multiple radicles, indicating the possibility of multiple embryos.

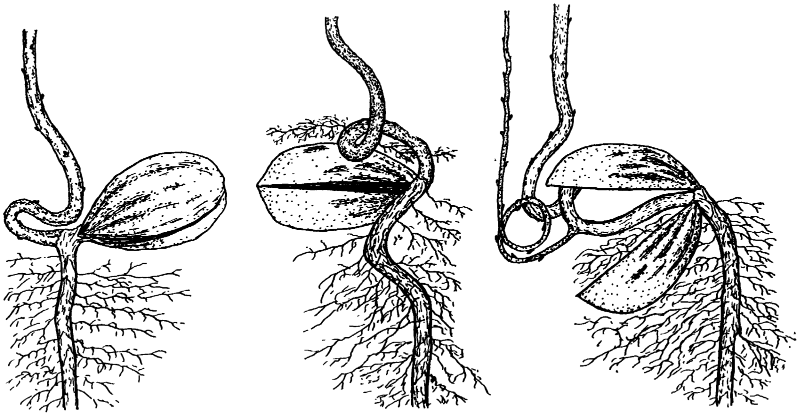

FIGURE 17.—Three germinating pecan nuts in which the plumules apparently lost their sense of direction and did not go straight upwards.

PLUMULES OR RADICLES WITH LOST SENSE OF DIRECTION

Stems normally grow upward, but numerous instances have been observed in which they did not do this. Sometimes they turned in all possible directions before finally turning upward (figs. 17 and 18). Such behavior is apparently caused by environmental conditions which have not been determined.

LATERAL ROOTS WITH LOST SENSE OF DIRECTION

A few instances have been observed where lateral or fibrous roots grew in peculiar shapes, or in positions which eventually meant their death. Figure 19 shows a root making two complete circles. In another case one root grew through another root.

ROOTS FROM COTYLEDONS

Roots are normally produced from other roots and sometimes from stems, but it is abnormal for them to be produced on cotyledons. Many times a mass of callus develops on the cotyledons near the point of attachment of the young seedling. From this callus have developed fibrous roots that function normally.

DISCUSSION

Many orchards have been thinned, and others should be thinned, because of competition among the trees. Competition begins earlier and becomes more intense with roots than with branches. The overlapping of the extremities of a few of the longest roots does not mean that thinning should follow immediately. In fact it is only when the roots meet between the rows that the soil area has become completely available to the trees. The condition existing in an orchard after the trees have been set 50 feet apart each way for about 15 years seems to approach the ideal so far as complete utilization of the soil is concerned.

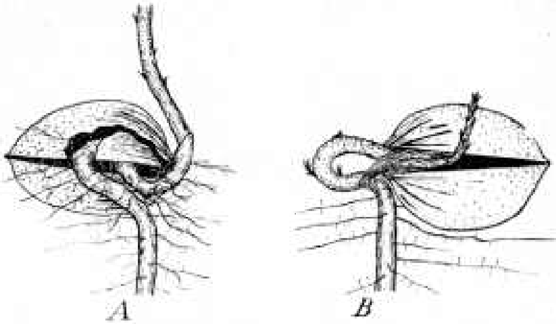

FIGURE 18.—*A*, Germinating pecan nut in which the radicle grew into the nut and then out again; *B*, germinating nut in which the plumule grew into the nut then out again.

The most economical use of fertilizers and the most advantageous types of cultivation can be carried on only when the horizontal and vertical extent of the tree roots is known. After the soil has become completely populated with roots it seems that all areas of the orchard

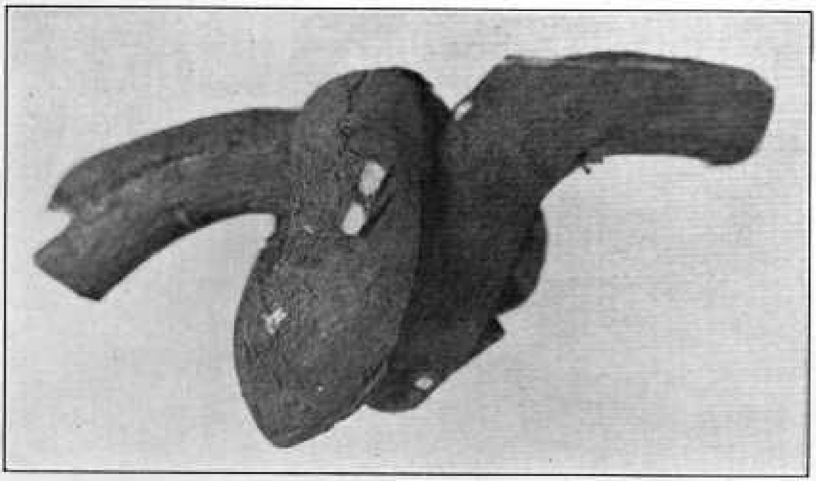

FIGURE 19.—A much curled, large pecan root which would probably have strangled itself within a few more years.

should be given equal fertilizing and cultivating treatment. The depth of cultivation will depend on the season of the year and condition of the orchard. Each cultivation disturbs feeding roots, and it is only when the good otherwise done more than compensates for the destruction of roots that the total effect of the operation is profitable. Each cultivation should have a specific object.

The time of applying fertilizers and the amount to be applied cannot be judged from a study of the roots alone. However, it is important to remember that roots grow throughout the winter, and if erosion is eliminated fertilizers can profitably be applied in the fall. The fact that roots are almost completely inactive during droughts of several weeks duration in the summer is important. At this time of the year the nuts should be making rapid growth, and the entire leaf area of the tree must be provided with moisture when there is little to be had. All available means should be used to provide enough moisture to maintain some growth throughout the summer.

SUMMARY

The spread of pecan roots in the soil is about twice that of the branches of the same tree. Roots seldom grow more than 5 feet deep in pecan orchards in Georgia.

There is a concentration of feeding roots near the surface of the soil, where they are repeatedly killed by droughts, freezes, and injuries from cultivating implements. Fibrous roots are short in length and short-lived. They are quickly replaced when growing conditions again become favorable.

Root pruning brought about either by transplanting or by cultivation causes branching and may be advantageous.

Young pecan roots may be divided into two classes, namely, large and small roots, each possessing distinct anatomical characters. Most small roots are mycorrhizal.

Pith is present only in taproots.

Root hairs are absent from pecan roots of all classes.

A distinct epidermis is absent from pecan roots.

The number of cells composing the various regions of individual roots is exceedingly variable.